

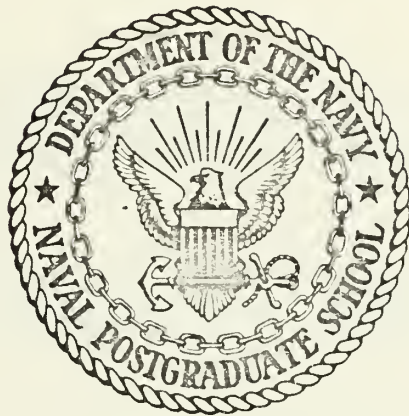
THE EFFECT OF IONOSPHERIC TILT ON  
RADIO DIRECTION FINDING POSITION  
ESTIMATES

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# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

The Effect of Ionospheric Tilt on  
Radio Direction Finding Position Estimates

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Radio Direction Finding Position Estimates

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## ABSTRACT

It is generally accepted that the ionosphere tilts; that is to say, an isoionic layer is not at constant height above the surface of the earth. Ionospheric tilt has the effect of deflecting a radio ray out of its great-circle plane and returning it to earth at an angle not that of the true bearing from a receiver to a transmitter. The magnitude of error introduced by this effect on radio direction finding (RDF) position estimates was studied in this paper. A model assigning a tilt bias of less than three degrees to each RDF station bearing was constructed. Analysis of a six-station RDF network revealed that this amount of tilt has negligible effect on point estimates of location and their confidence regions.





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## I. INTRODUCTION

Long range radio direction finding (RDF) is the art of determining the geographical position of a transmitter of unknown location by measuring the azimuthal angle of arrival (bearing) of a radio ray at several receiver sites and estimating the location of the transmitter by a form of triangulation. RDF techniques typically are based on the following two assumptions: 1) The earth is modeled sufficiently well by a true sphere, and 2) An observed bearing varies from true bearing by random error which is distributed normally (gaussian) with mean zero. The model is  $O = T + e$ , where  $O$  = observed bearing,  $T$  = true bearing and  $e$  = normal error associated with the receiver.

This investigation was concerned with the possibility of the existence of a non-trivial error due to ionospheric reflection superimposed on true bearing. The model hypothesized was  $O = T + B + e$ , where  $B$  is a random variable which is normally distributed about a non-zero mean. This component changes the mean of the distribution of the observed bearings from  $T$  to  $T + b$ , where  $b$  is the mean of  $B$ .

It is well known that reflecting layers in the ionosphere are not of equal height above the surface of the earth. This produces an ionospheric tilt which can provide





the component B. There are at least two major obstacles to modeling this effect:

1) Non-predictable traveling wave disturbances and the random phenomena which produce them keep the ionosphere in a constant state of flux, and

2) There does not exist a sufficiently extensive monitoring network to completely map electron densities in the ionosphere. These obstacles are discussed in the sequel together with general discussion on the effects of ionospheric tilt on RDF bearings and the estimated positions derived from those bearings. A model is presented and computer simulation is used to demonstrate the tilt effect on estimated location and confidence regions.



## II. IONOSPHERIC PHENOMENA

### A. GENERAL DISCUSSION

The ionosphere is a region of electrically charged (ionized) air beginning about 25 miles above the surface of the earth. Radio waves can travel long distances by being refracted in the ionosphere and returned to earth. It is the refracted ray that is received at the RDF site. The degree of ionization and the distribution of the charged particles is not constant with respect either to time or geographical location. This inconsistency results in refraction of a ray in a different manner from one instant of time to another for a given signal over a given path.

Very grossly the ionosphere may be thought of as a sea; that is, layers are not completely flat but contain ripples like waves on an ocean. In addition to the small-scale phenomena that compound inconsistent refraction: 1) First-order solar effects and 2) Traveling wave disturbances. The nature and effect of these concepts are discussed first followed by citation of some experimental support.

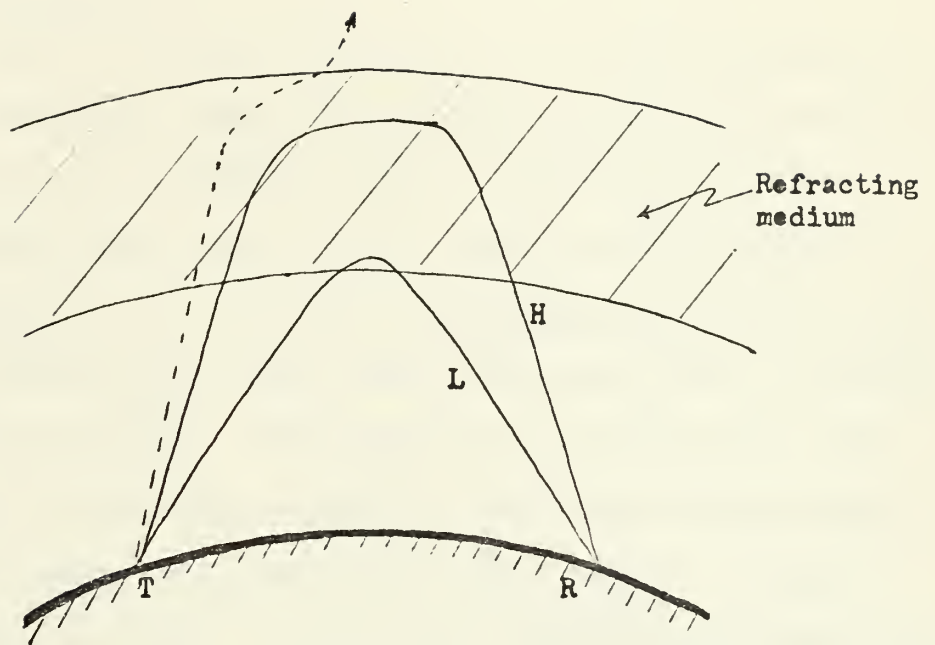
### B. REMARKS ON PROPAGATION

Although it is convenient to think of the ionosphere as a mirror-like reflecting surface, and such an interpretation is sufficient for some purposes, in actuality rays are bent or refracted in the ionosphere before being returned to earth. The amount of bending or the time a ray spends



in the ionosphere before being returned to earth depends in a complicated way on wave frequency, magnetic field and depth of penetration. In Figure 1, L represents "low-angle" refraction and H "high-angle". It is seen that rays arrive at the receiver, R, at correspondingly different elevation (vertical angle). It is also intuitive that the high-angle ray spends more time in the ionosphere since it penetrates deeper. In the sequel, reference will be made to three layers, E, F1 and F2. In a smooth undisturbed ionosphere, the F layers typically reflect both a high and a low ray as in Figure 1 whereas the E layer typically reflects only one ray. Figure 1 illustrates "one-hop" transmission. Two-hop rays (and higher degree hops) result from reflection at the surface of the earth back into the ionosphere which again returns the ray to earth at a different geographical location. Terminologically, a one-hop low-angle ray reflected at the F1 region will be designated 1F1L. A two-hop F2 high-angle ray will be 2F2H. Similarly, 2E will refer a two-hop ray reflected at the E layer. For further treatment of propagation phenomena the reader is referred to any of the number of textbooks on the subject. Two texts recommended are Kelso (1964) and Davies (1965). Also Ames (1964) contains an excellent brief discussion of propagation relating to the effect of tilt on bearing angle.





Radio ray propagation modes

FIGURE 1





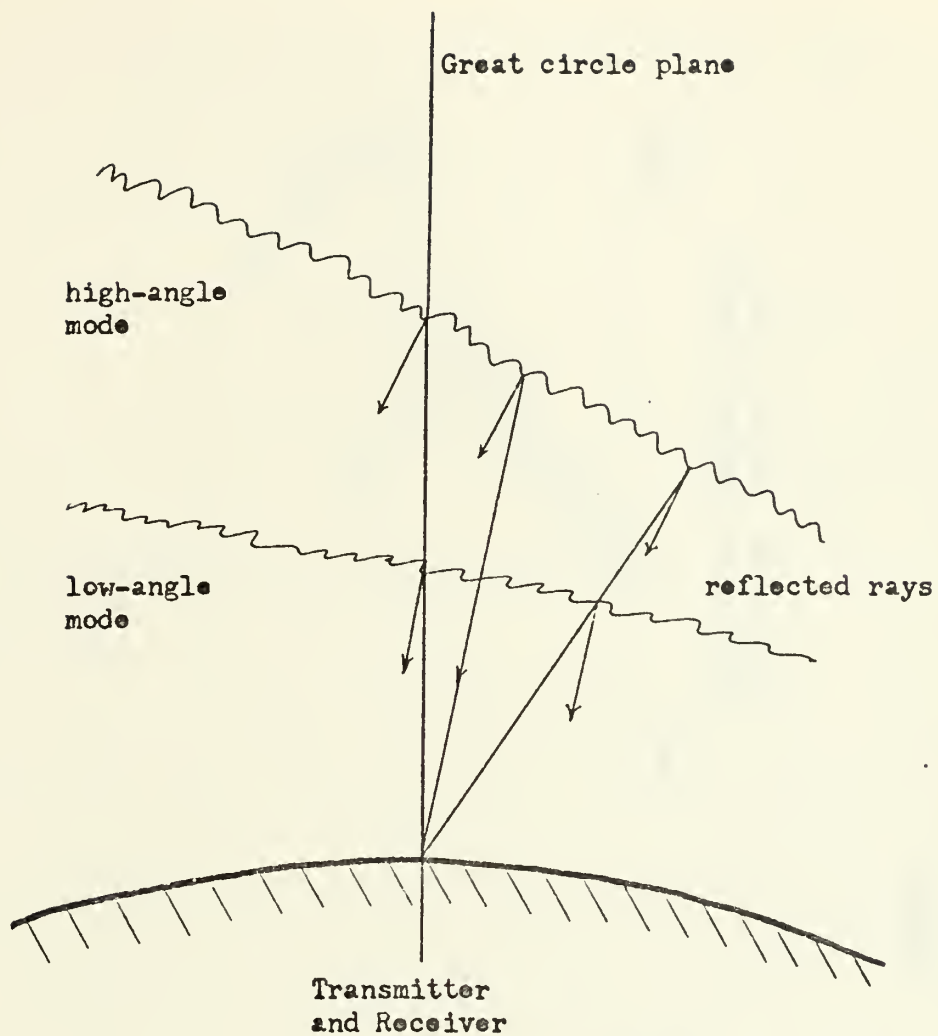
### C. FIRST ORDER SOLAR EFFECTS

Air particles in the ionosphere are ionized by ultraviolet rays from the sun and to a less extent by charged particles from the sun. Therefore the angle at which the sun's rays pass through the ionosphere determines the degree of ionization.

If allowed to ignore the effects of traveling disturbances, magnetism, earth surface and wind conditions one could say that an isoionic layer of the ionosphere is highest above the surface of the earth at the equator and decreases in altitude with increasing latitude because the angle between the sun's rays and local zenith increases as latitude increases. The result is a north-south tilt. Furthermore, ionization increases with increasing height and higher layers tilt more than lower layers. Figure 2 exaggerates the point. If the four possible rays reflected from the F layers are simultaneously received at one point one would expect each to arrive on a slightly different bearing. Figure 3a illustrates the difference in elevation angles and Figure 3b shows difference in azimuthal angles of arrival for the four rays.

In addition to this latitudinal effect there exists an east-west tilt. Electron density is highest at local noon and lowest at local midnight. There is constant change throughout the day and changes are very pronounced at ionospheric sunrise and sunset. Bramley (1956) estimated the east-west diurnal tilt change rate to be on the order

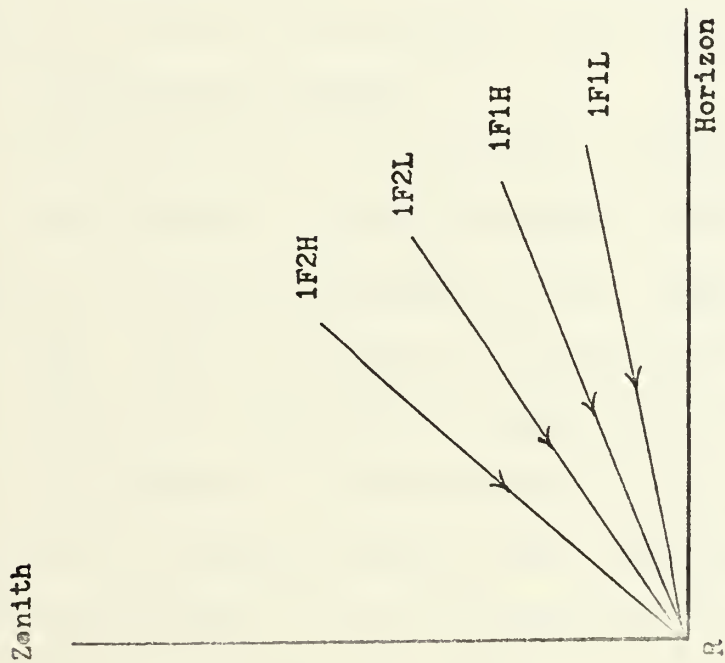




The effect of tilt on reflection  
of a ray from ionosphere

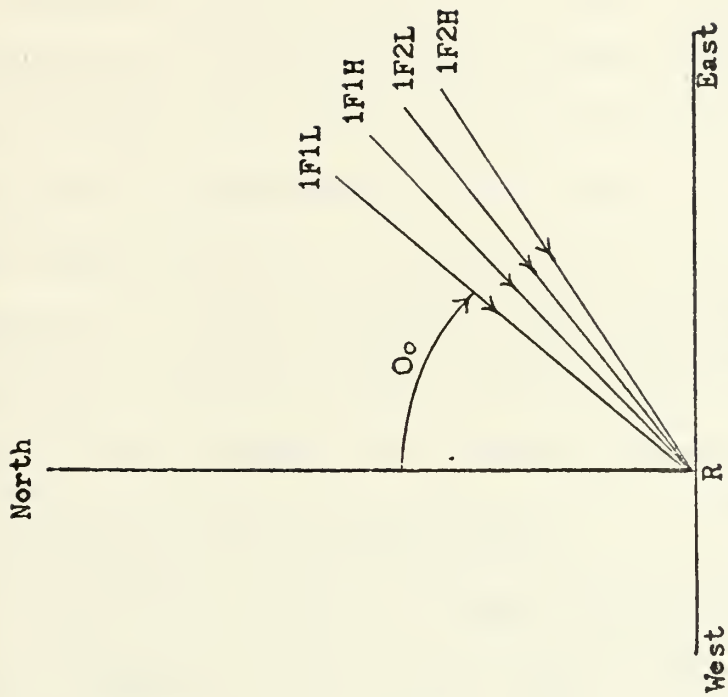
FIGURE 2





Side view at receiver showing  
elevation angle of propagation modes

a.



Top view at receiver showing  
azimuths for different modes

b.

FIGURE 3



of 0.2 degrees per hour. He does not distinguish between sunrise and sunset hours and periods of less change.

Similar to the diurnal tilt there exists a seasonal variation as the earth rotates around the sun and the sun's direct rays vary between the Tropic of Cancer and the Tropic of Capricorn. This effect is considered by most experimentors to be quite minor and slow to change compared to diurnal effects. Munro and Heisler (1963) summarize existing thought on the magnitude and directionality of both diurnal and seasonal effects.

#### D. TRAVELING WAVE DISTURBANCES

There are a number of other factors directly influencing the shape of an isoionic layer. The ionosphere over land is considerably different than it is over sea. The earth's magnetic field causes drag in the F-layer plasma and it varies highly. There are winds, thermal, and coriolis effects. One more phenomenon, traveling disturbances, will be discussed briefly.

Much literature exists on the subject of traveling wave disturbances. Several articles contain composite reviews of existing thought and past experiments and conclusions. One of the best of these is Detert (1965). (See also Munro and Heisler (1963) and Heisler (1965)).

A disturbance is characterized by an increase or decrease in electron density over background profiles. In early experiments traveling disturbances were included in a broad category called ionospheric storms. As more





sophisticated measuring equipment became available they became known as traveling wave disturbances and attempts were made to measure their size and velocities, and to predict them. A wide range of sizes and velocities have been reported. Hewish (1951, 1952) reports observing lengths (longitudinal extents) from 2-10 kilometers. Bramley (1953, 1955, 1956) observed velocities from 90 to 1300 km./hr. Chan and Villard (1962) reported disturbances from 1300 km. to over 2000 km. in length and velocities from 1450 to 2750 km./hr. Heisler (1963) shrewdly points out that size and velocity observations depend heavily on the method of measurement.

Causes of disturbances can be known (e.g., observable sun storms) or unknown. Chan and Villard believed the large disturbances they observed to have resulted from the same event that caused a coincidental change in the earth's magnetic field.

#### E. EXPERIMENTAL SUPPORT OF THE TILT CONCEPT

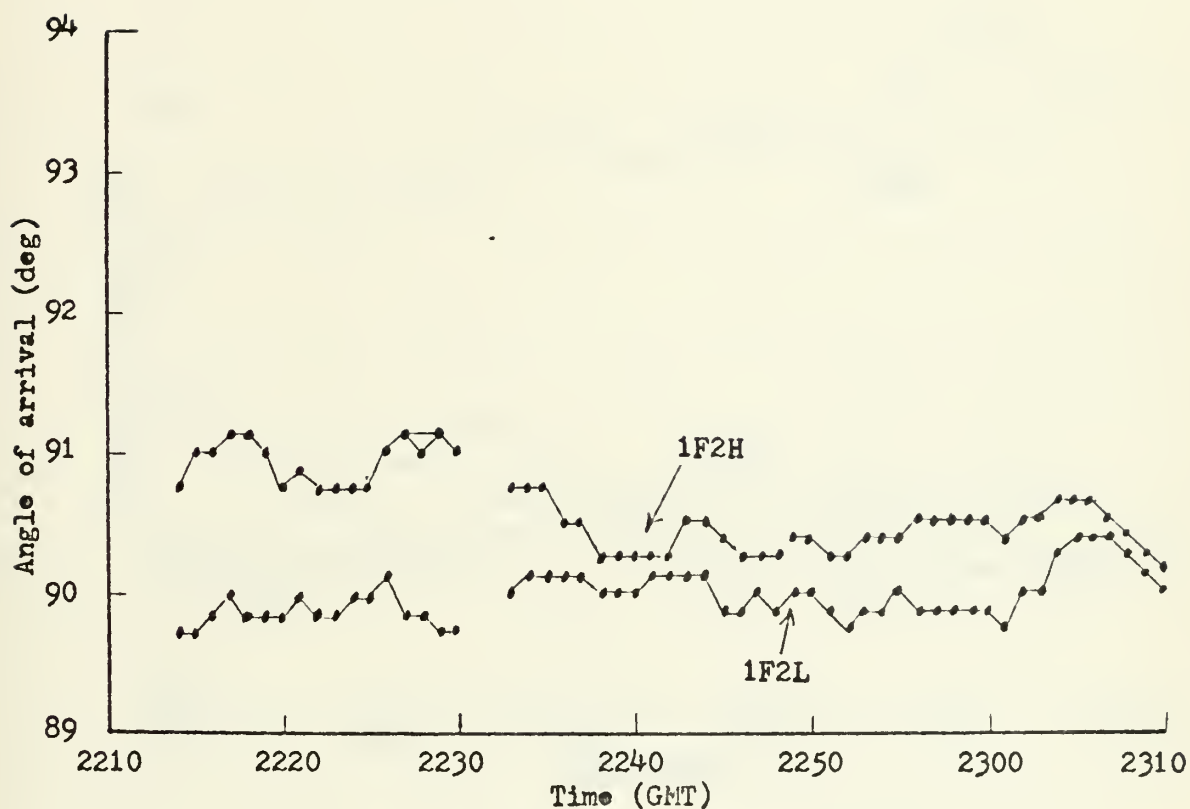
The results of three experiments will be presented in support of the existence of a non-zero mean bearing error. Sweeney (1970) measured the azimuthal pattern realized by a 256-element 2.5 km. broadside array receiving HF signals propagated over a 2600 km. east-west path. It was found that high rays tend to arrive south of low rays. Sweeney hypothesized that this tendency is a consequence of ionospheric tilts having north-south slopes which increase with altitude. This hypothesis was confirmed by



modeling the ionosphere in a computer ray-tracing program. Figure 4 and Figure 5 are reproduced from Sweeney's report. The true transmitter bearing was 90 degrees. In Figure 4 it can be seen that the 1F2L ray oscillates about the true bearing during undisturbed conditions. Sweeney summarizes that low-angle rays are accurate to the resolution of his antenna system; that is, one cannot discern a non-zero mean component of error in the low-angle rays. Sweeney also concludes that deviations occur mainly in reflection from the earth. If this is in fact the case one can draw the following conclusions: 1) deflection out of a great circle plane will not be measurable in a one-hop low-angle ray, 2) a high-angle ray will be observed noticeably south of the low-angle ray, and 3) multiple-hop rays will have more error due to reflections from the earth's surface. It must be kept in mind that Sweeney's two-hop rays were being reflected by the Rocky Mountains, an unusually rough reflecting surface.

Bredex (1963) was concerned with round-the-world (RTW) propagation. But his comments on the direct ray (Stanford, California to Champaign, Illinois) are of interest. The direct ray is defined to be the signal received via the shorter of the two great circle paths. Bredex observed that bearings fluctuated about a daily mean. The winter means were north of true bearing and displayed a southerly trend until they swung south of true bearing in March. With ten data points Bredex was able to fit a curve

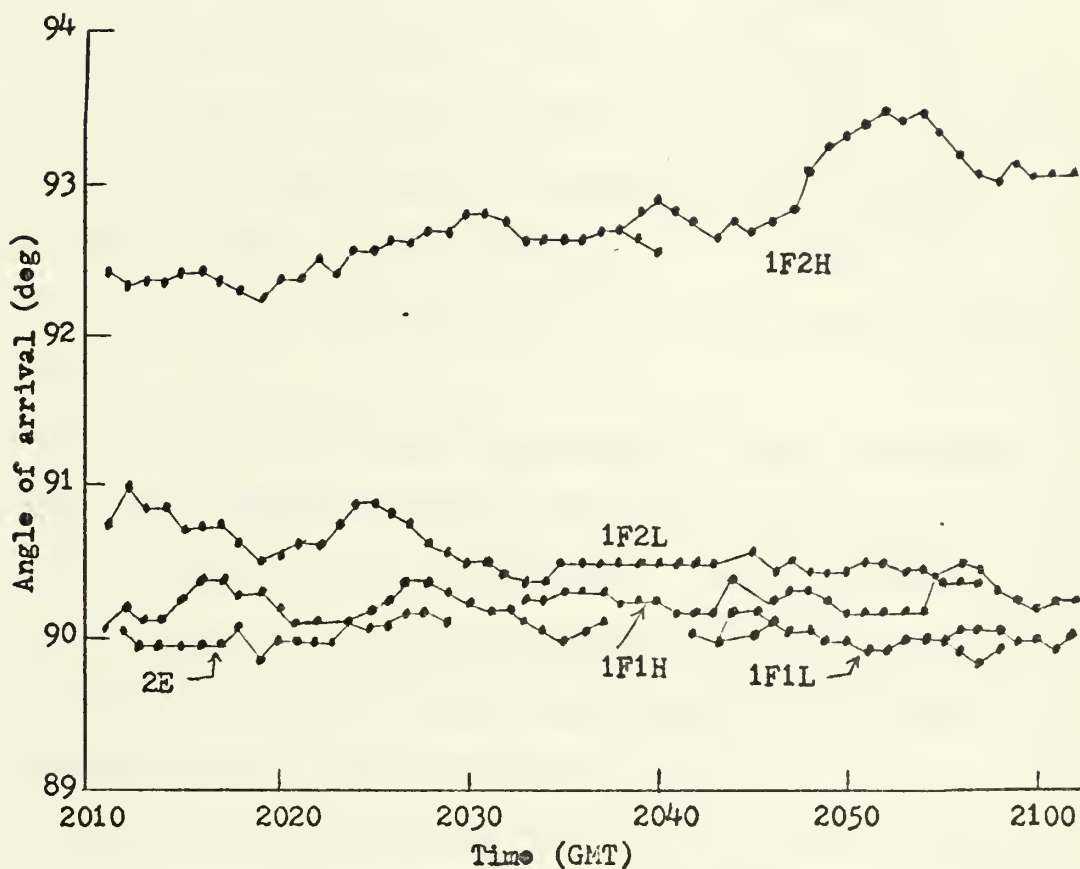




Plot of data collected by Sweeney (1970) showing high-angle ray arriving south of low-angle ray. The data were taken at 23 MHz on 25 August 1969. True bearing was 90 degrees.

FIGURE 4





Plot of data collected by Sweeney (1970) illustrating the difference in azimuth of different propagation modes. The data were taken at 14.5 MHz on 30 September 1969. True bearing was 90 degrees.

FIGURE 5





which crossed true bearing on 21 March, the vernal equinox. The conclusion is obvious even if somewhat speculative. Mildly stated, bearing means are sensitive to seasonal change. One other Bredek observation is worth noting here. Variation in RTW bearings was centered "a few degrees" south of the direct bearings. This is consistent with Sweeney's conclusion. Since the RTW ray has traveled much farther than the direct ray and is definitely multi-hop one expects to observe more variation in it. And with Sweeney's hypothesis one expects it to arrive south of the direct ray.

An unpublished experiment conducted at Naval Security Group Activity, Skaggs Island, California, showed the existence of an east-west diurnal tilt. Bearings were taken at two minute intervals on a signal transmitted from Hawaii during ionospheric sunrise and sunset. The data were analyzed by an autocorrelation function. Over a period of two hours the bearings failed to become statistically independent; that is to say, the bearings showed a definite trend to slide in one direction and not fluctuate about a cumulative mean. Similar experiments were conducted during undisturbed day and night conditions. The results were similar to Bramley and Ross (1951). Bramley (1953, 1955) and Bain (1955). Bearings showed a slow (up to 20 minutes) quasi-cyclic fluctuation about a mean in addition to rapid second-to-second fluctuation.



### III. THE MODEL

There does exist a deterministic element of bearing error. At least it can be said that there exists a component of error that has a determinable non-zero mean. The goal of this thesis is to determine the effect of this non-zero mean component B on RDF "fixes" (estimated transmitter location) and probability statements about these fixes.

According to Dr. Villard<sup>1</sup> (private communication 30 November 1971) the present state of technology is such that the non-zero mean component can be measured to almost any accuracy desired. What is lacking is the total commitment of effort and equipment to measure such a bias. In the absence of this commitment one may account for the error by modeling and statistical methods.

#### A. QUALITATIVE FEATURES

The most severe effect of ionospheric tilt is from east-west tilt at ionospheric sunrise and sunset. At other times of the day east-west tilt is very gradual. No attempt is made to account for sunrise and sunset tilt in this model. It is suggested, however, that this tilt should be

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<sup>1</sup>Dr. O. G. Villard, Jr., of Stanford University, is Chairman of the Special Committee on Electronics, a panel of the Naval Research Advisory Committee.



modeled by an error with positive mean for bearings in the third and fourth quadrants and a negative mean for bearings in the first and second quadrants at sunrise and oppositely at sunset. Between sunrise and sunset (and sunset and sunrise) east-west tilt is modeled sufficiently well with mean tilt equal to zero.

The degree of north-south tilt is more consistent than the diurnally periodic east-west tilt. The ionosphere tilts west to east in the morning and east to west in the afternoon whereas a north to south tilt exists throughout the day. In the sequel error due to tilt,  $B$ , is that produced by north-south tilt.

The model is restricted to rays reflected by an ionosphere between sunrise and sunset and to RDF stations and targets located in the northern hemisphere. It was constructed to represent conditions at mid-latitudes and it is assumed to be sufficiently accurate for all latitudes for which it is used in collection of data for this thesis.

The model contains two components of error. One is the usual random error and the other is due to tilt,  $B$ . The tilt component can be reduced to an unbiased random component by inserting a zero mean.

The model assigns a positive mean to error in bearings from zero to 180 degrees and a negative mean to bearings from 180 to 360 degrees. The error is assumed normal. Absolute value of the mean decreases with increasing distance due to the following two assumptions. It was assumed



that the receiver could not distinguish high-angle rays from low-angle rays. As a result the bearing measured is due to some unknown combination of high and low-angle rays. It was further assumed that the low-angle ray varies about the true bearing and the high-angle ray is the sole contributor to error due to tilt. High-angle rays are attenuated more rapidly than are low-angle rays. It follows that the greater the distance the less effect on bearing will there be due to the high-angle ray and the less the deviation due to tilt.

A systematic standard deviation is assigned to each RDF station. It is the basis of the dispersion of both random error,  $e$ , and tilt error,  $B$ . For use as a parameter in determining  $e$ , it increases with increasing distance (see Pope (1970)). For use as a parameter of  $B$  it decreases with increasing distance. Intuitively, the longer a ray is exposed to error-producing elements the more dispersion one expects in its distribution. This explains the increase of the parameter, call it  $s$ , with distance for  $e$ . A different argument applies to  $B$ . It is claimed that the dispersion of  $B$  is directly proportional to  $b$ , the mean of  $B$ . The quantity  $b$  is in some sense a measure of the strength of the effects that produce error due to tilt. The higher the value taken on by  $b$  the more influence on bearing has the high-angle ray. Using the same argument as for  $s$  (i.e., more exposure means higher variability) one concludes that the higher the  $b$  the greater the variance of





B. The parameter supplied in the model multiplies  $s$  by  $b$  to serve as the standard deviation of  $B$ . When  $b$  is zero due to great distance (complete attenuation of the high-angle ray)  $s$  is used as the standard deviation of  $B$ .

A final qualitative feature of the model recognizes the facts that mean error due to tilt is not the same for different bearings taken simultaneously from one site and tilt is not sloped exactly north-south. Predictions of actual slope at a given point in the ionosphere are extremely gross and quite inappropriate for a given instant of time. Also the high-angle ray is mixed with the low-angle ray in some unknown proportion. All of these effects are accounted for in the model by introducing a maximum value parameter  $b'$  (see Table 1) and multiplying it by a uniform random variable to produce  $b$ .

## B. QUANTITATIVE FEATURES

The maximum  $b'$  was assigned values as a function of distance according to Table 1. The values were assigned with some uneasiness but an attempt to justify them follows.

For distances less than 50 miles it was assumed that a ground wave is predominant and there is no effect from ionospheric tilt. At distances greater than 3600 miles the high-angle ray was assumed completely dissipated so that once again there is no deflection due to tilt. Sweeney (1970) observed high-angle rays that arrived approximately three degrees south of low-angle rays along an east-west propagation path (see Figure 4 and Figure 5).



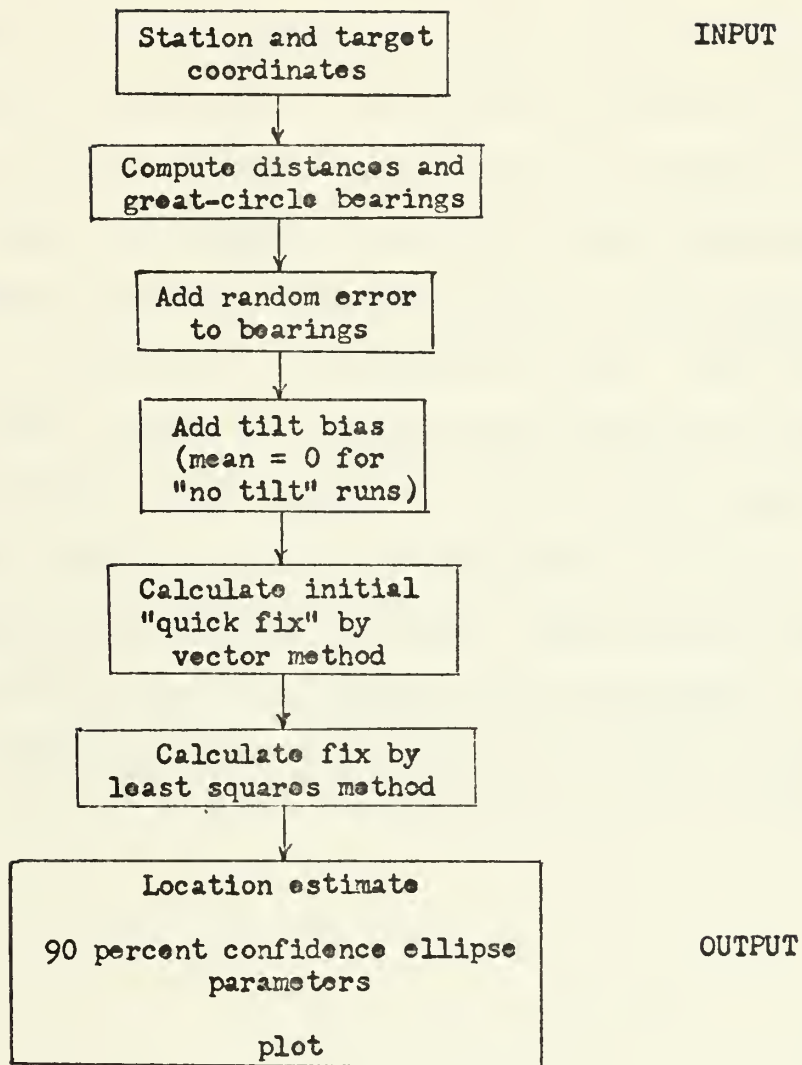
He modeled this phenomenon with an alpha-Chapman layer in the Jones (1966) three-dimensional ray-tracing computer program using average density data during undisturbed conditions. The results supported the hypothesis that the high-angle ray arrives approximately three degrees south of the low-angle ray for that particular 90 degree - 270 degree path. It is acknowledged that the maxima assigned to the distance categories between 900 miles and 3600 miles are artificial as are the categories themselves. But the assignments are sufficient to illustrate the effect of a component of error due to tilt and they are consistent with the qualitative discussion above.



#### IV. COMPUTER SYNTHESIS

The model was programmed in the Fortran IV language and computer simulation was employed to evaluate the effect of the non-zero component of error on the location of a fix point and the size and shape of the confidence regions generated by a standard RDF fix technique. Inputs to the program were station and target coordinates and a station systematic standard deviation. True bearings were computed and random and tilt error was superimposed on them. Fix points were computed by a vector method (Pope 1971) and the least squares method (Daniels, 1951 and Kukes and Starik, 1964). Two methods of obtaining confidence regions were available, chi-square regions and bivariate normal regions. Only the latter was used. Two random number generators were used to determine bearing error. One selected uniform random variates in the interval (0,1) while the other selected normal random variates for a given mean and standard deviation. Both generators are those recommended by Naylor, Balintfy, Burdick and Chu (1966). The basic steps in the simulation are shown in Figure 6.





Basic steps in computer simulation

FIGURE 6





## V. SIMULATION

A network of six RDF stations (Table II) took bearings on five targets (Table III). One hundred fixes were computed for each of the targets assigning only random error to the bearings. An additional 100 fixes were computed for each target with the model assigning to each bearing a component of error due to ionospheric tilt. For each set of 100 fixes, means and standard deviations were computed for latitude and longitude of the fix point and the major semiaxis and minor semiaxis and axis of rotation of the 90 percent confidence ellipse. Additionally, the fix points were plotted on a graph with rectangular coordinates. This procedure was repeated 25 times for each target.



## VI. RESULTS AND ANALYSIS

The sample means and standard deviations for each simulation run were tabulated in Tables IV to XIII. Figures 7 through 12 are selected samples of plots of fix locations. Meaningful statistical inferences and the validity of the model require that the samples collected be random. But the sample mean latitudes for Omaha, Gimli and Veracruz follow a definite trend and overwhelmingly fail the run test for randomness. It is interesting to note that the mean latitudes for these three targets are the only sets of values that fail the test for randomness (with the exception of the very stable minor semiaxis values). Even for these targets the mean longitudes show no trend whatever. In order to more clearly determine the randomness of the samples of positions, it was observed that the data are matched pairs of latitude and longitude. The data were reduced to single observations  $D(i) = \text{longitude}(i) - \text{latitude}(i)$ . The  $D(i)$  for the Omaha samples are tabulated in Table XIV. At significance level .05 the hypothesis that the  $D(i)$  constitute a random sample is accepted.

The objective of this thesis has been met without further statistical examination. Differences between extreme mean locations measure in the low tenths of degrees, just several miles. The systematic effect of tilt is insignificant from a practical point of view.



One important observation is that the standard deviations of the Omaha axes of rotation are quite large. Although in the Omaha example major and minor semiaxes are quite similar in magnitude, a variation from one extreme rotation angle to the other involves a displacement of approximately 25 percent of the area of the confidence region (crossed area in Figure 13).



## VII. CONCLUSIONS

Fix points and confidence regions were calculated from sets of bearings containing only random error and compared to the points and regions calculated from sets of bearings to which a component of error due to ionospheric tilt had been added. This component was considered a normal random variable.

The effect of superimposing a tilt error on bearings on the least squares method of computing estimated location and confidence regions from a six-station RDF network is negligible for a mean error due to tilt of less than or equal to three degrees with standard deviation less than three degrees.

The most intriguing development was that only in the case where the target was completely surrounded by stations did the angular orientation of the confidence region vary appreciably. Tilt played no role in this variability.





## VIII. REMARKS

The model presented was only a gross approximation to the effect of tilt. There are ways available to more accurately model the ionosphere. Predictions of ionospheric characteristics exist in several forms. Ionospheric Predictions, published by the Institute for Telecommunications Sciences and Aeronomy (ITSA), is a monthly periodical which contains numerical maps of maximum usable frequency at zero range (MUF(ze-ro)) and MUF(4000km.) for the F2 layer. In conjunction with other publications (e.g., National Bureau of Standards (NBS) Circular 462) it is possible to approximate virtual height of the F2 layer with respect to geographical location and time of day. The NBS Technical Note 40 series is published quarterly and contains predictions of ionospheric electron density. These can be used to construct a model based on the Chapman layer. (See Barnum (1968) p. 75 and Haydon and Lucas (1968)) With these aids the ionosphere can be modeled more accurately but in view of the results of this thesis it is suggested that an attempt to do so for RDF objectives would prove unprofitable.

The mathematical treatment of the RDF problem is by no means new. The theory was well presented by Stansfield (1947) and Daniels (1951). Kukes and Starik (1964) present a more lengthy and detailed discussion of the same basic theory. Burt, Kaplan, Keenly, Reeves, and Shaffer



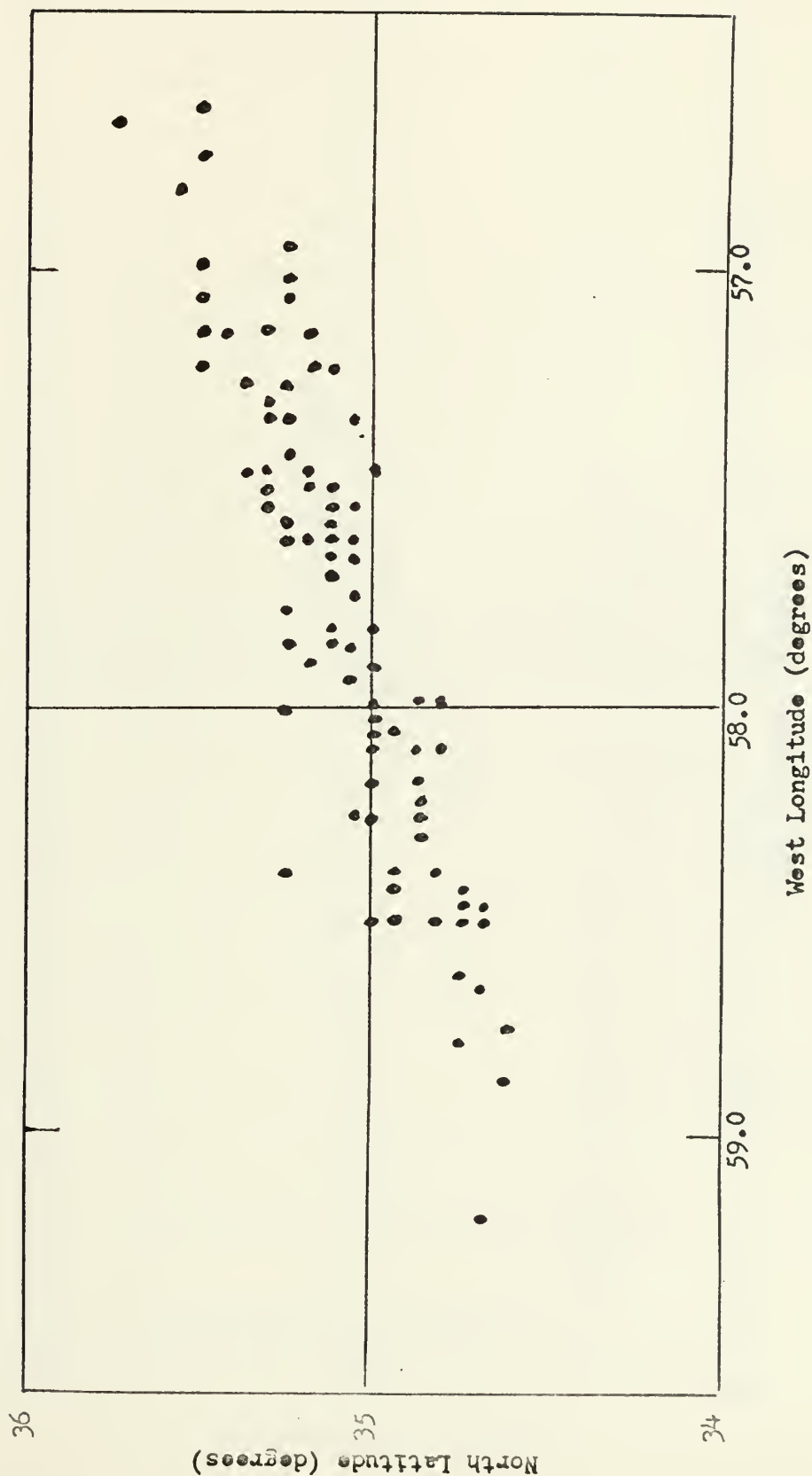
(1966) further defined terms and presented techniques for handling the general position finding problem. Existing techniques assume the earth to be a true sphere and employ spherical trigonometry. In fact, the earth is slightly oblate so that over long distances a correction to the spherical treatment is necessary for accurate location. In RDF the problem becomes the difference in bearing between a spherical great circle and a spheroidal geodesic. Using parameters for the Clark Spheroid of 1866 the difference at mid latitude was found to be as great as 0.5 degrees. An additional characteristic is that the geodesic may start north of the great circle then cross to south as distance increases. In practice the detrimental effect of the spherical assumption is considered negligible. Thomas (1970) discussed spheroids and presented solutions to a geodesic which are adaptable to both manual and computer calculation.



## IX. SUGGESTIONS FOR FURTHER STUDY

Although the cases simulated in this report were chosen to demonstrate the effect of tilt on RDF fix points, one interesting side-effect provided an outfall. The orientation of a confidence ellipse can change considerably the geographical area covered by that region. Furthermore, it appears that the variability of orientation depends on the location of the target relative to the RDF network. The variability of orientation of confidence regions can have tremendous impact on the validity of probability statements based on RDF techniques. A study of the effect on confidence regions of target location and network configuration is suggested. The orientation of a confidence region depends on the magnitude of variance of each bearing used to calculate the fix point. A study to determine the sensitivity of this orientation as a function of variance in individual bearings may prove valuable.





Plot of 100 fixes  
Target: Atlantic  
Mode: Tilt  
True position: 58.0W 35.0N

FIGURE 7

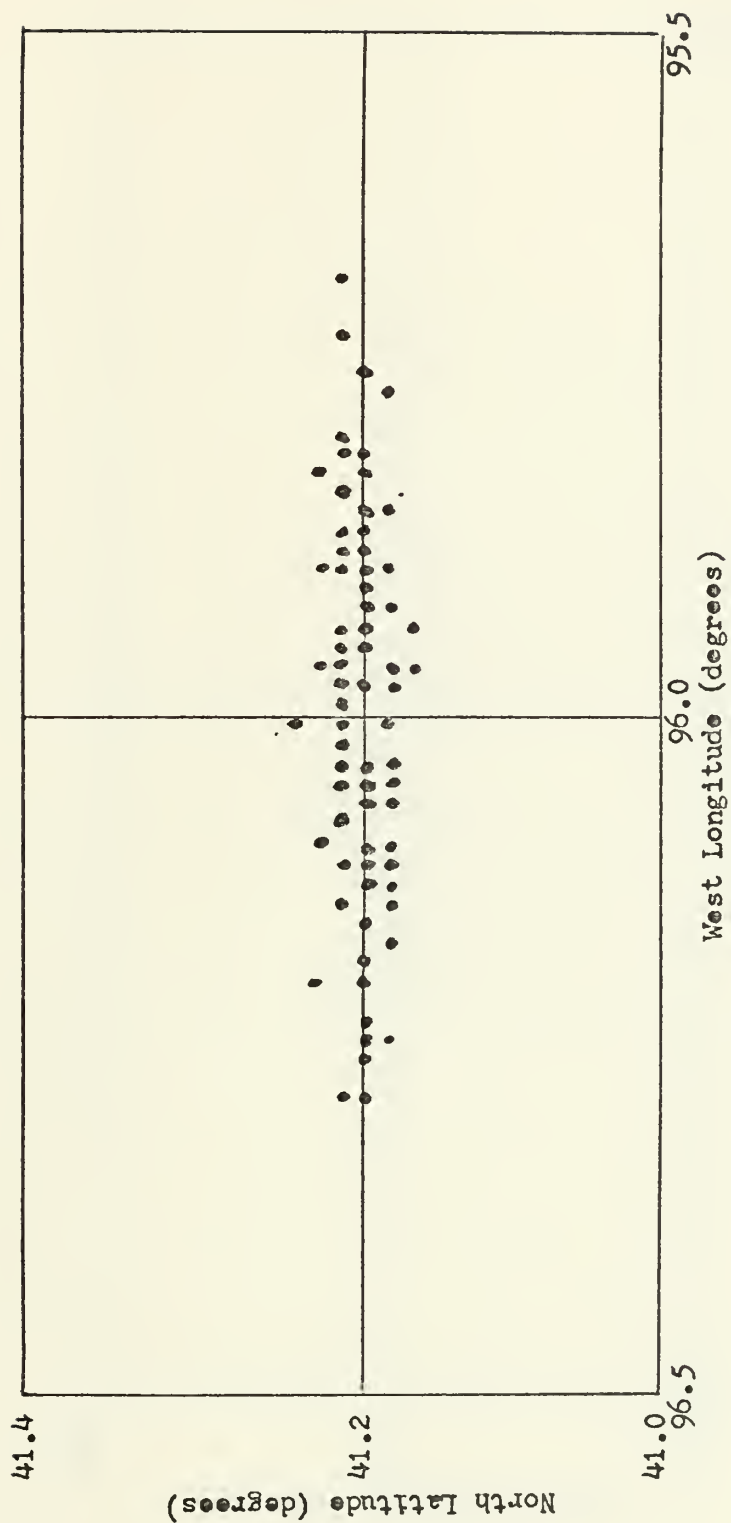






FIGURE 8

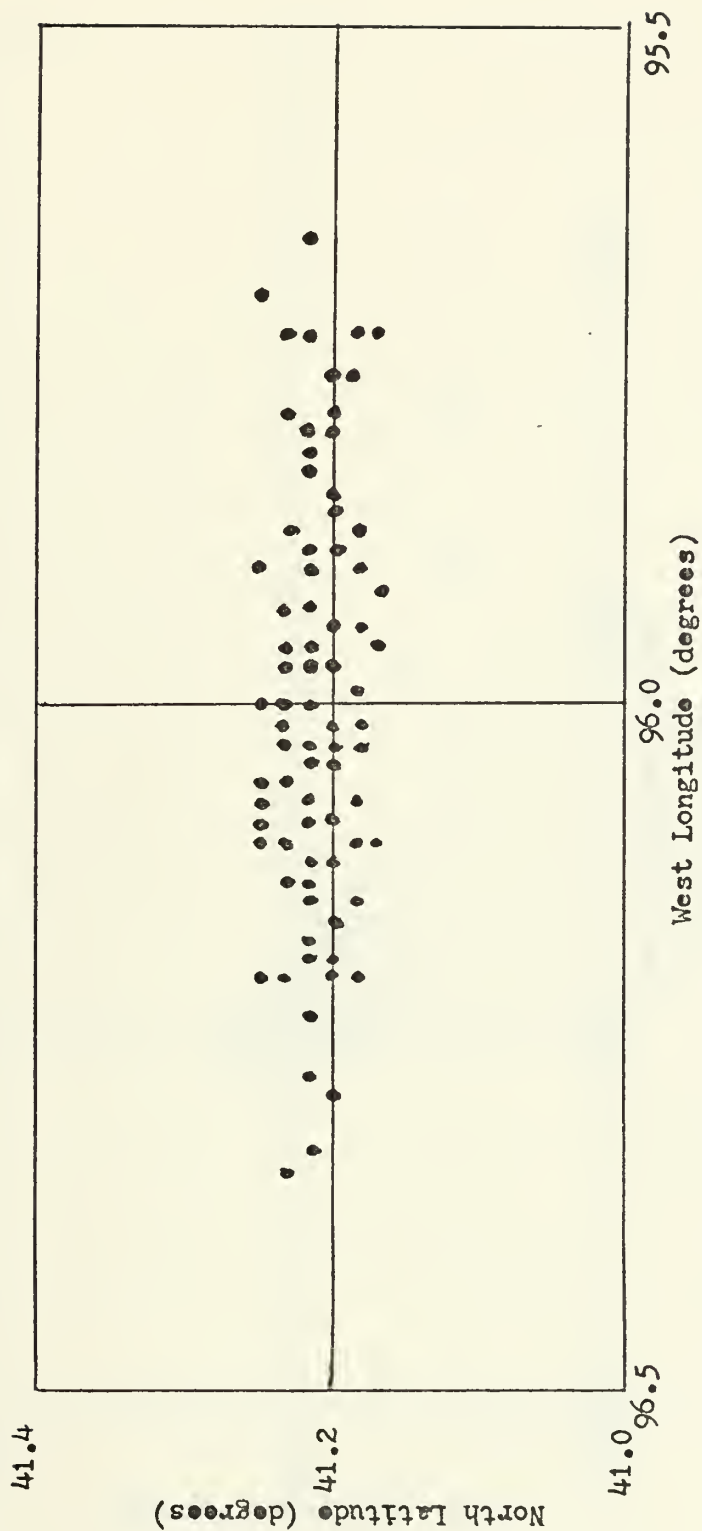




Plot of 100 fixes  
 Target: Omaha  
 Mode: Tilt  
 True position: 96.0W 41.2N

FIGURE 9

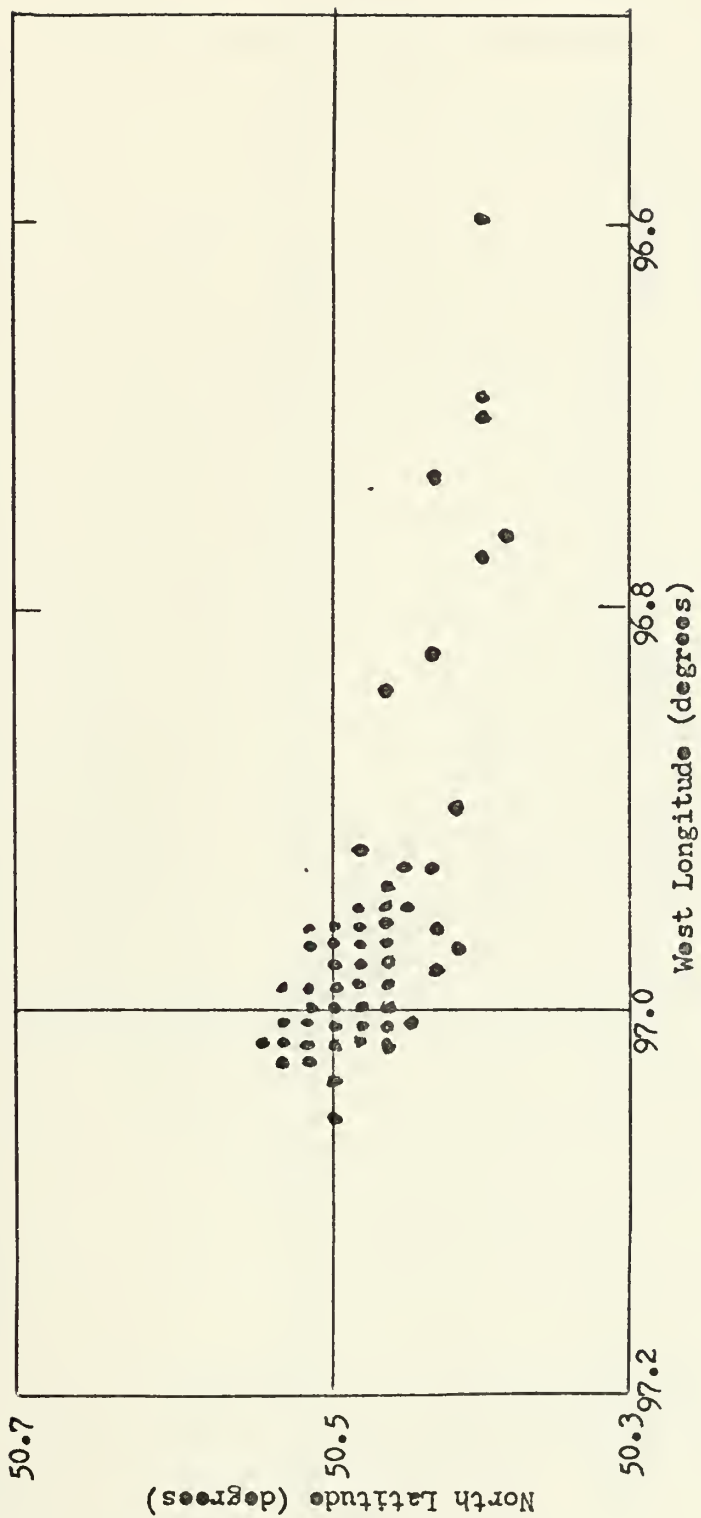




Plot of 100 fixes  
 Target: Omaha  
 Mode: No tilt  
 True position: 96.0W 41.2N

FIGURE 10



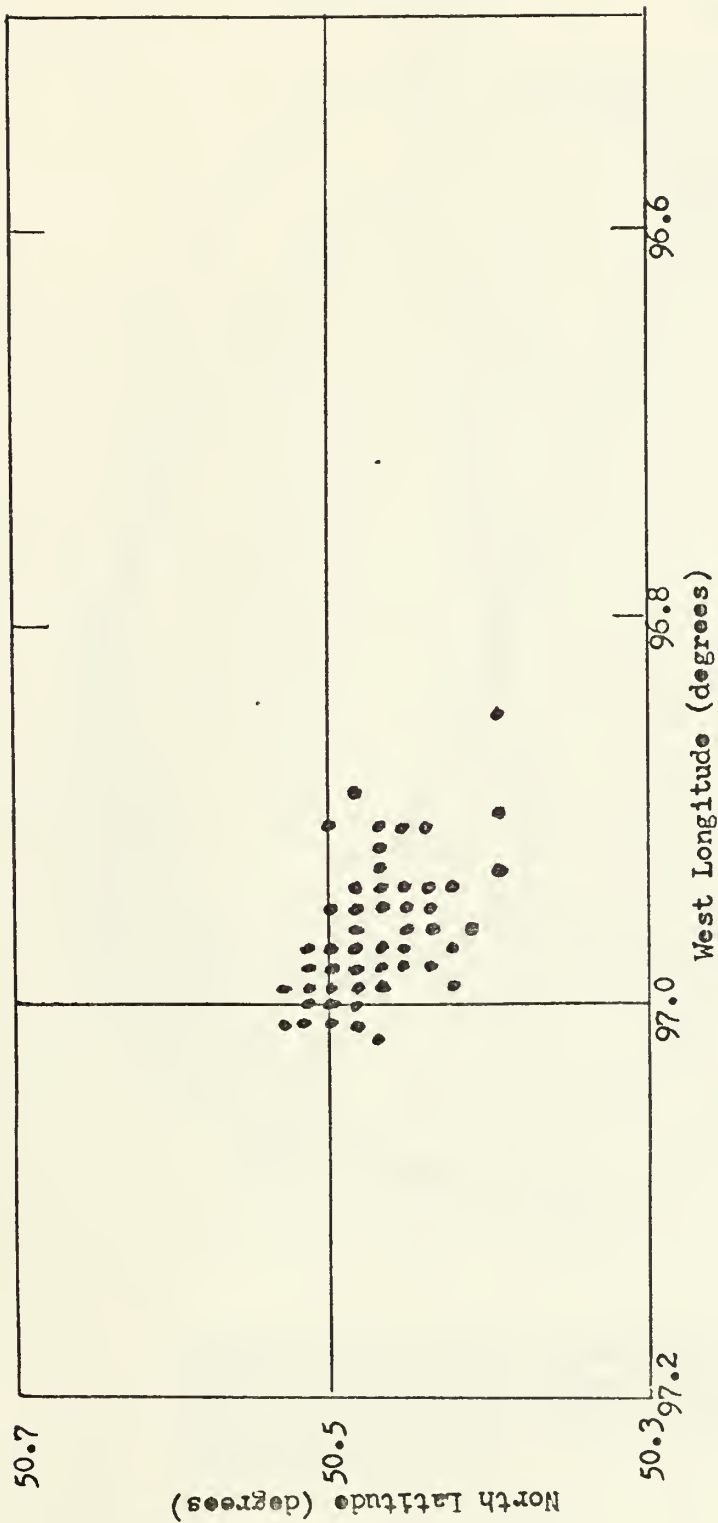


Plot of 100 fixes  
 Target: Gimli  
 Mode: No tilt  
 True position: 97.0W 50.5N

FIGURE 11



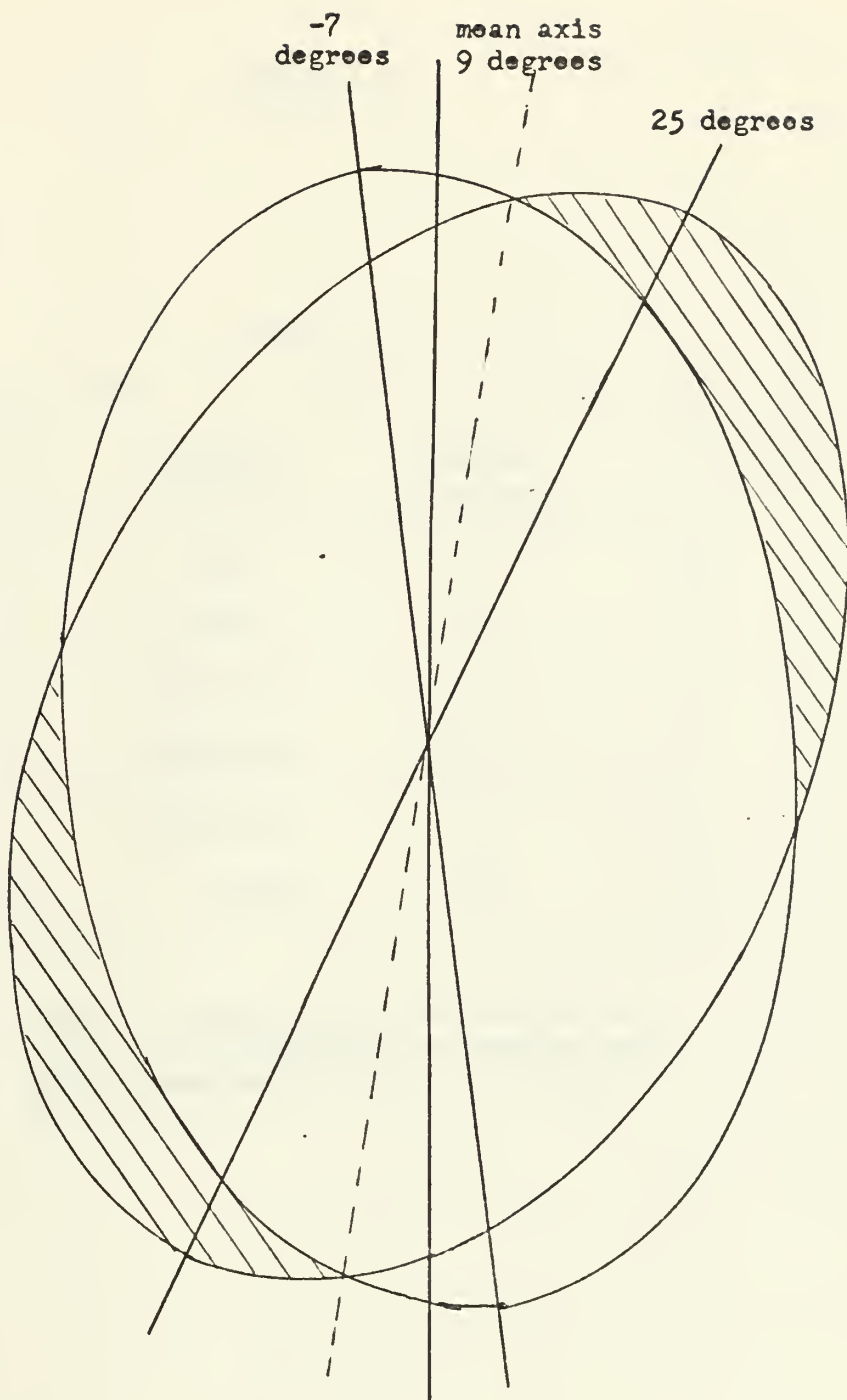




Plot of 100 fixes  
 Target: Gimli  
 Mode: Tilt  
 True position: 97.0W 50.5N

FIGURE 12





Shaded area is that displaced by a 32 degree rotation of axis of ellipse with semimajor axis = 2.92 and semi-minor axis = 1.90.

FIGURE 13



APPENDIX A

TABLE 1

| Distance<br>(miles) | b'<br>Maxima<br>(degrees) |
|---------------------|---------------------------|
| 0-50                | 0.0                       |
| 50-900              | 3.0                       |
| 900-1800            | 2.5                       |
| 1800-2700           | 2.0                       |
| 2700-3600           | 1.5                       |
| > 3600              | 0.0                       |

Maxima assigned for the calculation of means for the component of bearing error due to ionospheric tilt as a function of distance.



TABLE II

| Station     | Location |       |
|-------------|----------|-------|
|             | Lat.     | Lon.  |
| Miami       | 25.6     | 80.2  |
| Boston      | 42.4     | 71.0  |
| Grand Falls | 48.0     | 94.0  |
| Seattle     | 47.5     | 122.5 |
| Los Angeles | 34.0     | 118.5 |
| Houston     | 30.0     | 97.9  |

Composition of RDF network for simulation

TABLE III

| Target   | Location |       |
|----------|----------|-------|
|          | Lat.     | Lon.  |
| Omaha    | 41.2     | 96.0  |
| Veracruz | 18.5     | 96.0  |
| Gimli    | 50.5     | 97.0  |
| Atlantic | 35.0     | 58.0  |
| Pacific  | 40.0     | 135.0 |

Targets used in simulation





TABLE IV

| Location |       |        |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|--------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.   | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 41.206   | 0.022 | 96.039 | 0.124 | 1.295                         | 0.006 | 1.189             | 0.005 | 11.124              | 3.694 |
| 41.191   | 0.019 | 95.964 | 0.136 | 1.296                         | 0.006 | 1.189             | 0.005 | 11.599              | 3.538 |
| 41.187   | 0.029 | 96.019 | 0.149 | 1.295                         | 0.008 | 1.190             | 0.006 | 10.742              | 3.506 |
| 41.170   | 0.023 | 95.996 | 0.138 | 1.296                         | 0.007 | 1.189             | 0.006 | 10.454              | 3.755 |
| 41.164   | 0.021 | 95.960 | 0.138 | 1.294                         | 0.007 | 1.190             | 0.006 | 10.343              | 3.957 |
| 41.156   | 0.021 | 95.997 | 0.155 | 1.294                         | 0.007 | 1.191             | 0.006 | 10.948              | 3.242 |
| 41.147   | 0.022 | 95.984 | 0.138 | 1.295                         | 0.008 | 1.190             | 0.006 | 10.517              | 2.936 |
| 41.139   | 0.020 | 95.999 | 0.150 | 1.295                         | 0.008 | 1.190             | 0.006 | 10.253              | 4.116 |
| 41.124   | 0.022 | 95.972 | 0.157 | 1.296                         | 0.007 | 1.189             | 0.006 | 10.562              | 3.756 |
| 41.115   | 0.023 | 95.991 | 0.148 | 1.296                         | 0.007 | 1.189             | 0.005 | 10.811              | 3.188 |
| 41.199   | 0.019 | 95.998 | 0.144 | 1.297                         | 0.006 | 1.188             | 0.005 | 11.686              | 3.596 |
| 41.199   | 0.025 | 95.991 | 0.146 | 1.294                         | 0.006 | 1.197             | 0.007 | 11.108              | 3.970 |
| 41.185   | 0.024 | 95.993 | 0.142 | 1.294                         | 0.007 | 1.190             | 0.006 | 11.106              | 3.539 |
| 41.177   | 0.021 | 96.012 | 0.127 | 1.295                         | 0.006 | 1.190             | 0.005 | 10.027              | 3.753 |
| 41.165   | 0.019 | 96.021 | 0.145 | 1.296                         | 0.006 | 1.189             | 0.005 | 11.190              | 3.386 |
| 41.155   | 0.023 | 96.023 | 0.140 | 1.295                         | 0.007 | 1.189             | 0.005 | 10.842              | 3.645 |
| 41.148   | 0.024 | 96.014 | 0.128 | 1.295                         | 0.007 | 1.190             | 0.006 | 10.445              | 3.506 |
| 41.133   | 0.020 | 95.998 | 0.140 | 1.295                         | 0.006 | 1.190             | 0.005 | 9.985               | 4.764 |
| 41.123   | 0.021 | 96.005 | 0.157 | 1.297                         | 0.007 | 1.188             | 0.005 | 11.283              | 3.528 |
| 41.115   | 0.025 | 95.971 | 0.131 | 1.295                         | 0.008 | 1.190             | 0.006 | 9.916               | 3.823 |
| 41.108   | 0.022 | 96.017 | 0.125 | 1.296                         | 0.006 | 1.189             | 0.004 | 10.046              | 3.053 |
| 41.098   | 0.020 | 95.992 | 0.130 | 1.295                         | 0.006 | 1.189             | 0.005 | 11.090              | 3.961 |
| 41.090   | 0.021 | 96.010 | 0.137 | 1.296                         | 0.007 | 1.189             | 0.005 | 11.408              | 3.400 |
| 41.089   | 0.019 | 96.001 | 0.112 | 1.293                         | 0.007 | 1.191             | 0.005 | 9.772               | 4.383 |
| 41.077   | 0.030 | 96.014 | 0.130 | 1.295                         | 0.008 | 1.190             | 0.006 | 10.921              | 3.399 |

Sample means and standard deviations

Target: Omaha

Mode: No tilt

All values in degrees



TABLE V

| Location |       |        |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|--------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.   | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 41.195   | 0.018 | 96.031 | 0.151 | 1.294                         | 0.006 | 1.191             | 0.005 | 8.126               | 3.743 |
| 41.192   | 0.014 | 95.973 | 0.166 | 1.294                         | 0.006 | 1.190             | 0.005 | 7.483               | 3.683 |
| 41.181   | 0.015 | 96.009 | 0.117 | 1.293                         | 0.007 | 1.191             | 0.006 | 7.818               | 3.582 |
| 41.166   | 0.015 | 96.014 | 0.014 | 1.296                         | 0.006 | 1.189             | 0.005 | 9.518               | 4.011 |
| 41.156   | 0.016 | 95.974 | 0.119 | 1.295                         | 0.007 | 1.190             | 0.005 | 8.567               | 4.143 |
| 41.153   | 0.017 | 95.978 | 0.145 | 1.294                         | 0.006 | 1.191             | 0.005 | 7.644               | 3.484 |
| 41.138   | 0.013 | 95.980 | 0.141 | 1.297                         | 0.006 | 1.188             | 0.005 | 8.300               | 3.593 |
| 41.139   | 0.021 | 95.974 | 0.147 | 1.294                         | 0.006 | 1.191             | 0.005 | 7.454               | 4.493 |
| 41.126   | 0.016 | 95.957 | 0.116 | 1.295                         | 0.005 | 1.190             | 0.004 | 9.060               | 4.178 |
| 41.120   | 0.022 | 95.980 | 0.147 | 1.294                         | 0.006 | 1.190             | 0.005 | 8.832               | 4.195 |
| 41.106   | 0.019 | 95.986 | 0.164 | 1.294                         | 0.006 | 1.191             | 0.004 | 8.493               | 5.166 |
| 41.097   | 0.019 | 95.996 | 0.127 | 1.295                         | 0.007 | 1.190             | 0.005 | 8.874               | 4.049 |
| 41.091   | 0.017 | 95.960 | 0.122 | 1.294                         | 0.006 | 1.190             | 0.004 | 8.641               | 3.905 |
| 41.082   | 0.017 | 95.938 | 0.141 | 1.294                         | 0.006 | 1.190             | 0.005 | 8.977               | 3.561 |
| 41.071   | 0.016 | 95.956 | 0.160 | 1.294                         | 0.006 | 1.191             | 0.005 | 8.913               | 3.594 |
| 41.190   | 0.016 | 95.948 | 0.139 | 1.295                         | 0.006 | 1.190             | 0.005 | 8.802               | 3.578 |
| 41.177   | 0.020 | 96.016 | 0.135 | 1.295                         | 0.006 | 1.190             | 0.005 | 7.813               | 3.698 |
| 41.173   | 0.022 | 95.983 | 0.160 | 1.293                         | 0.006 | 1.191             | 0.005 | 7.959               | 3.757 |
| 41.161   | 0.019 | 95.993 | 0.176 | 1.295                         | 0.007 | 1.190             | 0.005 | 8.329               | 3.804 |
| 41.153   | 0.015 | 95.969 | 0.146 | 1.294                         | 0.006 | 1.191             | 0.005 | 7.836               | 4.222 |
| 41.142   | 0.013 | 95.968 | 0.114 | 1.295                         | 0.005 | 1.190             | 0.004 | 9.612               | 3.686 |
| 41.138   | 0.017 | 95.970 | 0.120 | 1.294                         | 0.006 | 1.191             | 0.004 | 8.833               | 3.758 |
| 41.127   | 0.015 | 96.005 | 0.130 | 1.295                         | 0.006 | 1.190             | 0.005 | 9.050               | 3.817 |
| 41.108   | 0.019 | 95.965 | 0.125 | 1.293                         | 0.005 | 1.191             | 0.004 | 8.143               | 3.953 |
| 41.112   | 0.015 | 95.971 | 0.160 | 1.296                         | 0.006 | 1.189             | 0.005 | 8.538               | 3.522 |

Sample means and standard deviations

Target: Omaha

Mode: Tilt

All values in degrees



TABLE VI

| Location |       |        |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|--------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.   | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 35.082   | 0.251 | 57.803 | 0.561 | 3.826                         | 0.089 | 0.900             | 0.001 | -25.747             | 0.280 |
| 35.027   | 0.225 | 57.918 | 0.535 | 3.820                         | 0.092 | 0.900             | 0.001 | -25.848             | 0.283 |
| 34.980   | 0.232 | 58.056 | 0.483 | 3.867                         | 0.069 | 0.899             | 0.001 | -25.821             | 0.260 |
| 35.025   | 0.227 | 57.913 | 0.560 | 3.836                         | 0.087 | 0.900             | 0.001 | -25.831             | 0.302 |
| 34.988   | 0.241 | 58.018 | 0.534 | 3.853                         | 0.089 | 0.900             | 0.001 | -25.874             | 0.301 |
| 35.020   | 0.201 | 57.850 | 0.506 | 3.828                         | 0.093 | 0.900             | 0.001 | -25.757             | 0.311 |
| 34.956   | 0.192 | 58.025 | 0.521 | 3.853                         | 0.101 | 0.900             | 0.001 | -25.857             | 0.303 |
| 34.954   | 0.220 | 58.013 | 0.519 | 3.838                         | 0.089 | 0.900             | 0.001 | -25.892             | 0.324 |
| 34.976   | 0.221 | 57.924 | 0.495 | 3.831                         | 0.071 | 0.900             | 0.001 | -25.859             | 0.259 |
| 34.972   | 0.240 | 57.894 | 0.592 | 3.821                         | 0.094 | 0.900             | 0.001 | -25.847             | 0.299 |
| 34.936   | 0.206 | 58.012 | 0.510 | 3.843                         | 0.095 | 0.900             | 0.001 | -25.866             | 0.300 |
| 34.943   | 0.194 | 57.869 | 0.466 | 3.812                         | 0.086 | 0.900             | 0.001 | -25.783             | 0.358 |
| 34.982   | 0.251 | 57.892 | 0.563 | 3.832                         | 0.090 | 0.900             | 0.001 | -25.919             | 0.324 |
| 34.932   | 0.242 | 57.864 | 0.551 | 3.820                         | 0.090 | 0.900             | 0.001 | -25.789             | 0.269 |
| 34.927   | 0.258 | 57.895 | 0.633 | 3.811                         | 0.098 | 0.900             | 0.001 | -25.867             | 0.322 |
| 34.938   | 0.218 | 57.807 | 0.578 | 3.812                         | 0.016 | 0.900             | 0.001 | -25.759             | 0.269 |
| 34.877   | 0.228 | 57.904 | 0.605 | 3.819                         | 0.101 | 0.900             | 0.001 | -25.801             | 0.321 |
| 34.903   | 0.249 | 57.888 | 0.542 | 3.813                         | 0.085 | 0.900             | 0.001 | -25.877             | 0.267 |
| 34.910   | 0.204 | 57.878 | 0.495 | 3.815                         | 0.089 | 0.900             | 0.001 | -25.891             | 0.302 |
| 34.839   | 0.240 | 58.013 | 0.590 | 3.829                         | 0.107 | 0.900             | 0.001 | -25.930             | 0.291 |
| 35.045   | 0.248 | 57.846 | 0.578 | 3.840                         | 0.107 | 0.900             | 0.001 | -25.670             | 0.308 |
| 35.026   | 0.211 | 57.945 | 0.541 | 3.841                         | 0.093 | 0.900             | 0.001 | -25.809             | 0.307 |
| 35.041   | 0.238 | 57.912 | 0.595 | 3.848                         | 0.092 | 0.900             | 0.001 | -25.758             | 0.329 |
| 35.001   | 0.210 | 57.952 | 0.581 | 3.836                         | 0.099 | 0.900             | 0.001 | -25.843             | 0.283 |
| 34.988   | 0.213 | 57.968 | 0.528 | 3.837                         | 0.092 | 0.900             | 0.001 | -25.838             | 0.352 |

Sample means and standard deviations

Target: Atlantic

Mode: No tilt

All values in degrees





TABLE VII

| Location |       |        |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|--------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.   | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 34.995   | 0.167 | 58.028 | 0.365 | 3.777                         | 0.085 | 0.901             | 0.001 | -26.142             | 0.219 |
| 35.023   | 0.135 | 57.952 | 0.320 | 3.772                         | 0.072 | 0.901             | 0.001 | -26.030             | 0.211 |
| 35.022   | 0.157 | 57.946 | 0.341 | 3.782                         | 0.071 | 0.901             | 0.001 | -26.070             | 0.197 |
| 35.001   | 0.115 | 57.921 | 0.270 | 3.756                         | 0.086 | 0.901             | 0.001 | -26.103             | 0.209 |
| 35.017   | 0.153 | 57.878 | 0.313 | 3.740                         | 0.090 | 0.901             | 0.001 | -26.168             | 0.228 |
| 34.962   | 0.158 | 57.950 | 0.401 | 3.752                         | 0.085 | 0.901             | 0.001 | -26.149             | 0.232 |
| 34.931   | 0.157 | 58.077 | 0.385 | 3.777                         | 0.068 | 0.901             | 0.001 | -26.220             | 0.254 |
| 34.979   | 0.161 | 57.950 | 0.384 | 3.781                         | 0.075 | 0.901             | 0.001 | -26.137             | 0.220 |
| 34.971   | 0.166 | 57.947 | 0.372 | 3.749                         | 0.096 | 0.901             | 0.001 | -26.220             | 0.211 |
| 34.970   | 0.186 | 57.891 | 0.411 | 3.744                         | 0.088 | 0.901             | 0.001 | -26.178             | 0.243 |
| 34.939   | 0.154 | 57.940 | 0.358 | 3.758                         | 0.078 | 0.901             | 0.001 | -26.165             | 0.246 |
| 34.925   | 0.140 | 57.947 | 0.309 | 3.752                         | 0.067 | 0.901             | 0.001 | -26.175             | 0.199 |
| 34.895   | 0.136 | 58.044 | 0.328 | 3.751                         | 0.074 | 0.901             | 0.001 | -26.241             | 0.205 |
| 34.927   | 0.161 | 57.907 | 0.342 | 3.741                         | 0.071 | 0.901             | 0.001 | -26.200             | 0.207 |
| 34.900   | 0.126 | 57.956 | 0.366 | 3.751                         | 0.079 | 0.901             | 0.001 | -26.201             | 0.221 |
| 35.046   | 0.111 | 57.933 | 0.270 | 3.772                         | 0.068 | 0.901             | 0.001 | -26.107             | 0.184 |
| 35.013   | 0.172 | 57.947 | 0.440 | 3.757                         | 0.098 | 0.901             | 0.001 | -26.128             | 0.251 |
| 34.977   | 0.142 | 58.023 | 0.346 | 3.778                         | 0.082 | 0.901             | 0.001 | -26.139             | 0.180 |
| 35.019   | 0.182 | 57.921 | 0.354 | 3.767                         | 0.084 | 0.901             | 0.001 | -26.131             | 0.215 |
| 35.026   | 0.151 | 57.877 | 0.384 | 3.768                         | 0.083 | 0.901             | 0.001 | -26.088             | 0.223 |
| 34.960   | 0.168 | 58.009 | 0.392 | 3.770                         | 0.088 | 0.901             | 0.001 | -26.186             | 0.224 |
| 35.004   | 0.119 | 57.882 | 0.293 | 3.745                         | 0.076 | 0.901             | 0.001 | -26.183             | 0.168 |
| 34.982   | 0.158 | 57.927 | 0.349 | 3.757                         | 0.081 | 0.901             | 0.001 | -26.163             | 0.201 |
| 34.952   | 0.174 | 57.928 | 0.348 | 3.744                         | 0.072 | 0.901             | 0.001 | -26.192             | 0.223 |
| 34.935   | 0.140 | 57.973 | 0.364 | 3.752                         | 0.083 | 0.901             | 0.001 | -26.214             | 0.225 |

Sample means and standard deviations

Target: Atlantic

Mode: Tilt

All values in degrees





TABLE VIII

| Location |       |         |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|---------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.    | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 40.024   | 0.152 | 135.044 | 0.502 | 3.552                         | 0.097 | 0.904             | 0.002 | 20.651              | 0.326 |
| 40.049   | 0.154 | 135.140 | 0.580 | 3.584                         | 0.105 | 0.904             | 0.002 | 20.721              | 0.289 |
| 40.013   | 0.181 | 134.981 | 0.703 | 3.583                         | 0.088 | 0.904             | 0.002 | 20.747              | 0.317 |
| 39.971   | 0.163 | 134.889 | 0.585 | 3.380                         | 0.087 | 0.904             | 0.001 | 20.658              | 0.397 |
| 40.027   | 0.183 | 135.083 | 0.641 | 3.584                         | 0.098 | 0.904             | 0.002 | 20.639              | 0.309 |
| 40.002   | 0.179 | 135.034 | 0.631 | 3.591                         | 0.096 | 0.903             | 0.002 | 20.633              | 0.333 |
| 40.008   | 0.148 | 135.001 | 0.522 | 3.592                         | 0.084 | 0.903             | 0.001 | 20.788              | 0.260 |
| 40.031   | 0.169 | 135.096 | 0.614 | 3.591                         | 0.084 | 0.903             | 0.001 | 20.692              | 0.359 |
| 39.980   | 0.160 | 134.884 | 0.562 | 3.596                         | 0.086 | 0.903             | 0.001 | 20.697              | 0.266 |
| 40.008   | 0.160 | 135.008 | 0.557 | 3.576                         | 0.093 | 0.904             | 0.002 | 20.699              | 0.326 |
| 40.011   | 0.143 | 135.016 | 0.549 | 3.602                         | 0.092 | 0.903             | 0.001 | 20.753              | 0.296 |
| 39.983   | 0.190 | 134.919 | 0.674 | 3.600                         | 0.093 | 0.903             | 0.002 | 20.723              | 0.292 |
| 40.037   | 0.179 | 135.110 | 0.639 | 3.610                         | 0.083 | 0.903             | 0.001 | 20.748              | 0.333 |
| 39.996   | 0.168 | 134.977 | 0.645 | 3.596                         | 0.097 | 0.903             | 0.002 | 20.674              | 0.308 |
| 39.965   | 0.186 | 134.906 | 0.647 | 3.589                         | 0.090 | 0.903             | 0.001 | 20.796              | 0.326 |
| 40.008   | 0.170 | 135.006 | 0.587 | 3.559                         | 0.083 | 0.904             | 0.001 | 20.654              | 0.284 |
| 40.028   | 0.168 | 135.028 | 0.625 | 3.620                         | 0.091 | 0.903             | 0.001 | 20.697              | 0.306 |
| 40.022   | 0.179 | 135.054 | 0.642 | 3.571                         | 0.069 | 0.904             | 0.001 | 20.693              | 0.293 |
| 40.000   | 0.203 | 135.030 | 0.754 | 3.593                         | 0.113 | 0.903             | 0.002 | 20.735              | 0.354 |
| 40.018   | 0.185 | 135.053 | 0.670 | 3.564                         | 0.076 | 0.904             | 0.001 | 20.684              | 0.341 |
| 40.032   | 0.203 | 135.090 | 0.721 | 3.568                         | 0.082 | 0.904             | 0.001 | 20.689              | 0.317 |
| 40.015   | 0.193 | 135.035 | 0.677 | 3.592                         | 0.078 | 0.903             | 0.001 | 20.702              | 0.327 |
| 40.008   | 0.194 | 134.998 | 0.616 | 3.598                         | 0.088 | 0.903             | 0.001 | 20.701              | 0.359 |
| 40.016   | 0.157 | 135.017 | 0.631 | 3.603                         | 0.084 | 0.903             | 0.001 | 20.739              | 0.306 |
| 40.025   | 0.144 | 135.032 | 0.583 | 3.582                         | 0.101 | 0.904             | 0.002 | 20.652              | 0.409 |

Sample means and standard deviations

Target: Pacific

Mode: No tilt

The dimension of all values is degrees



TABLE IX

| Location |       |         |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|---------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.    | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 40.000   | 0.102 | 134.963 | 0.417 | 3.425                         | 0.060 | 0.906             | 0.001 | 20.712              | 0.272 |
| 39.984   | 0.081 | 134.945 | 0.350 | 3.446                         | 0.064 | 0.906             | 0.001 | 20.698              | 0.268 |
| 39.982   | 0.074 | 134.901 | 0.281 | 3.456                         | 0.054 | 0.906             | 0.001 | 20.740              | 0.266 |
| 39.987   | 0.080 | 134.895 | 0.342 | 3.444                         | 0.072 | 0.906             | 0.001 | 20.686              | 0.201 |
| 39.997   | 0.081 | 134.987 | 0.346 | 3.447                         | 0.073 | 0.906             | 0.001 | 20.607              | 0.264 |
| 39.997   | 0.074 | 134.998 | 0.337 | 3.441                         | 0.067 | 0.906             | 0.001 | 20.623              | 0.233 |
| 39.968   | 0.075 | 134.867 | 0.298 | 3.435                         | 0.080 | 0.906             | 0.001 | 20.669              | 0.278 |
| 39.997   | 0.087 | 134.977 | 0.375 | 3.450                         | 0.069 | 0.906             | 0.001 | 20.705              | 0.258 |
| 40.001   | 0.094 | 134.971 | 0.327 | 3.440                         | 0.067 | 0.906             | 0.001 | 20.647              | 0.296 |
| 39.985   | 0.104 | 134.912 | 0.402 | 3.452                         | 0.077 | 0.906             | 0.001 | 20.699              | 0.301 |
| 40.033   | 0.084 | 135.077 | 0.357 | 3.453                         | 0.070 | 0.906             | 0.001 | 20.669              | 0.289 |
| 40.003   | 0.095 | 135.010 | 0.404 | 3.437                         | 0.076 | 0.906             | 0.001 | 20.608              | 0.313 |
| 40.002   | 0.077 | 134.985 | 0.302 | 3.437                         | 0.069 | 0.906             | 0.001 | 20.649              | 0.271 |
| 39.997   | 0.077 | 134.980 | 0.332 | 3.452                         | 0.082 | 0.906             | 0.001 | 20.617              | 0.262 |
| 40.020   | 0.100 | 135.043 | 0.409 | 3.462                         | 0.069 | 0.906             | 0.001 | 20.636              | 0.248 |
| 40.010   | 0.079 | 135.090 | 0.338 | 3.420                         | 0.073 | 0.906             | 0.001 | 20.598              | 0.324 |
| 39.996   | 0.102 | 135.009 | 0.383 | 3.438                         | 0.072 | 0.906             | 0.001 | 20.558              | 0.270 |
| 39.991   | 0.090 | 134.951 | 0.336 | 3.439                         | 0.057 | 0.906             | 0.001 | 20.674              | 0.336 |
| 39.996   | 0.084 | 134.934 | 0.296 | 3.452                         | 0.080 | 0.906             | 0.001 | 20.666              | 0.295 |
| 39.978   | 0.091 | 134.906 | 0.388 | 3.430                         | 0.072 | 0.906             | 0.001 | 20.676              | 0.274 |
| 39.997   | 0.081 | 134.958 | 0.351 | 3.453                         | 0.064 | 0.906             | 0.001 | 20.702              | 0.291 |
| 40.005   | 0.103 | 135.006 | 0.396 | 3.433                         | 0.080 | 0.906             | 0.001 | 20.580              | 0.268 |
| 39.999   | 0.090 | 134.954 | 0.353 | 3.451                         | 0.074 | 0.906             | 0.001 | 20.621              | 0.257 |
| 40.008   | 0.078 | 135.010 | 0.318 | 3.450                         | 0.067 | 0.906             | 0.001 | 20.653              | 0.282 |
| 39.984   | 0.093 | 134.908 | 0.347 | 3.463                         | 0.077 | 0.906             | 0.001 | 20.676              | 0.315 |

Sample means and standard deviations

Target: Pacific

Mode: Tilt

All values in degrees



TABLE X

| Location |       |        |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|--------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.   | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 50.483   | 0.024 | 96.970 | 0.063 | 1.415                         | 0.008 | 1.116             | 0.004 | 33.967              | 1.153 |
| 50.473   | 0.030 | 96.975 | 0.072 | 1.415                         | 0.010 | 1.116             | 0.005 | 34.088              | 1.068 |
| 50.460   | 0.032 | 96.977 | 0.051 | 1.418                         | 0.010 | 1.114             | 0.005 | 33.580              | 1.240 |
| 50.452   | 0.030 | 96.979 | 0.053 | 1.418                         | 0.009 | 1.114             | 0.004 | 33.743              | 1.353 |
| 50.439   | 0.045 | 96.962 | 0.112 | 1.417                         | 0.009 | 1.115             | 0.005 | 33.680              | 1.206 |
| 50.437   | 0.033 | 96.977 | 0.071 | 1.417                         | 0.008 | 1.115             | 0.004 | 33.703              | 1.262 |
| 50.424   | 0.039 | 96.970 | 0.086 | 1.418                         | 0.012 | 1.114             | 0.006 | 33.489              | 1.218 |
| 50.407   | 0.038 | 96.953 | 0.112 | 1.419                         | 0.010 | 1.114             | 0.005 | 33.275              | 1.059 |
| 50.401   | 0.033 | 96.977 | 0.053 | 1.419                         | 0.012 | 1.114             | 0.006 | 33.157              | 1.005 |
| 50.395   | 0.035 | 96.968 | 0.079 | 1.418                         | 0.010 | 1.114             | 0.005 | 33.297              | 1.050 |
| 50.389   | 0.034 | 96.975 | 0.067 | 1.420                         | 0.010 | 1.113             | 0.005 | 33.001              | 0.904 |
| 50.378   | 0.031 | 96.981 | 0.057 | 1.420                         | 0.010 | 1.113             | 0.005 | 33.439              | 1.312 |
| 50.376   | 0.025 | 96.988 | 0.026 | 1.421                         | 0.007 | 1.113             | 0.004 | 32.728              | 0.938 |
| 50.362   | 0.034 | 96.967 | 0.084 | 1.422                         | 0.011 | 1.112             | 0.005 | 32.943              | 1.148 |
| 50.359   | 0.038 | 96.962 | 0.124 | 1.421                         | 0.011 | 1.113             | 0.005 | 33.149              | 1.385 |
| 50.479   | 0.036 | 96.954 | 0.098 | 1.416                         | 0.008 | 1.115             | 0.004 | 33.913              | 1.191 |
| 50.468   | 0.037 | 96.962 | 0.105 | 1.416                         | 0.008 | 1.115             | 0.004 | 33.842              | 1.397 |
| 50.455   | 0.045 | 96.962 | 0.114 | 1.419                         | 0.011 | 1.114             | 0.005 | 33.076              | 1.331 |
| 50.455   | 0.031 | 96.975 | 0.061 | 1.418                         | 0.009 | 1.114             | 0.004 | 33.631              | 1.068 |
| 50.437   | 0.038 | 96.957 | 0.091 | 1.419                         | 0.011 | 1.114             | 0.005 | 33.528              | 1.213 |
| 50.424   | 0.037 | 96.949 | 0.113 | 1.419                         | 0.010 | 1.114             | 0.005 | 33.860              | 1.158 |
| 50.428   | 0.030 | 96.980 | 0.060 | 1.419                         | 0.009 | 1.114             | 0.004 | 33.467              | 1.151 |
| 50.419   | 0.024 | 96.986 | 0.034 | 1.418                         | 0.008 | 1.114             | 0.004 | 33.447              | 1.343 |
| 50.402   | 0.033 | 96.966 | 0.082 | 1.420                         | 0.010 | 1.113             | 0.005 | 33.309              | 1.092 |
| 50.404   | 0.027 | 96.985 | 0.031 | 1.416                         | 0.009 | 1.115             | 0.004 | 33.203              | 1.237 |

Sample means and standard deviations

Target: Gimli

Mode: No tilt

All values in degrees





TABLE XI

| Location |       |        |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|--------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.   | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 50.468   | 0.034 | 96.959 | 0.041 | 1.420                         | 0.010 | 1.113             | 0.005 | 30.952              | 1.273 |
| 50.462   | 0.026 | 96.970 | 0.027 | 1.418                         | 0.011 | 1.114             | 0.005 | 31.338              | 1.182 |
| 50.455   | 0.028 | 96.974 | 0.033 | 1.420                         | 0.007 | 1.113             | 0.003 | 31.278              | 1.099 |
| 50.439   | 0.030 | 96.963 | 0.032 | 1.420                         | 0.009 | 1.113             | 0.004 | 31.443              | 1.076 |
| 50.436   | 0.027 | 96.970 | 0.032 | 1.418                         | 0.007 | 1.114             | 0.004 | 31.448              | 1.239 |
| 50.427   | 0.028 | 96.962 | 0.064 | 1.419                         | 0.005 | 1.114             | 0.005 | 31.185              | 1.060 |
| 50.409   | 0.030 | 96.962 | 0.029 | 1.420                         | 0.009 | 1.113             | 0.004 | 30.843              | 1.022 |
| 50.410   | 0.029 | 96.971 | 0.031 | 1.419                         | 0.010 | 1.114             | 0.005 | 30.736              | 1.204 |
| 50.396   | 0.025 | 96.972 | 0.026 | 1.420                         | 0.008 | 1.113             | 0.004 | 30.712              | 1.002 |
| 50.388   | 0.028 | 96.969 | 0.025 | 1.420                         | 0.010 | 1.114             | 0.005 | 30.696              | 1.154 |
| 50.387   | 0.028 | 96.967 | 0.031 | 1.419                         | 0.012 | 1.114             | 0.006 | 30.510              | 1.168 |
| 50.369   | 0.035 | 96.965 | 0.031 | 1.421                         | 0.012 | 1.113             | 0.005 | 30.536              | 1.315 |
| 50.365   | 0.022 | 96.969 | 0.026 | 1.419                         | 0.009 | 1.114             | 0.004 | 30.440              | 1.038 |
| 50.355   | 0.021 | 96.974 | 0.026 | 1.419                         | 0.009 | 1.114             | 0.005 | 30.629              | 0.794 |
| 50.346   | 0.032 | 96.972 | 0.036 | 1.420                         | 0.010 | 1.113             | 0.005 | 30.179              | 1.065 |
| 50.463   | 0.032 | 96.975 | 0.031 | 1.418                         | 0.010 | 1.114             | 0.005 | 31.873              | 1.088 |
| 50.448   | 0.031 | 96.960 | 0.033 | 1.420                         | 0.010 | 1.113             | 0.005 | 31.076              | 1.044 |
| 50.445   | 0.026 | 96.967 | 0.027 | 1.418                         | 0.010 | 1.114             | 0.005 | 31.198              | 1.133 |
| 50.430   | 0.035 | 96.970 | 0.036 | 1.419                         | 0.010 | 1.114             | 0.005 | 31.175              | 1.151 |
| 50.428   | 0.024 | 96.968 | 0.034 | 1.418                         | 0.010 | 1.114             | 0.005 | 30.908              | 1.091 |
| 50.415   | 0.027 | 96.972 | 0.024 | 1.419                         | 0.009 | 1.114             | 0.004 | 31.053              | 1.140 |
| 50.409   | 0.026 | 96.975 | 0.030 | 1.419                         | 0.008 | 1.114             | 0.004 | 30.950              | 0.910 |
| 50.409   | 0.023 | 96.975 | 0.023 | 1.418                         | 0.008 | 1.114             | 0.004 | 30.913              | 1.137 |
| 50.385   | 0.033 | 96.964 | 0.032 | 1.420                         | 0.012 | 1.113             | 0.006 | 30.767              | 1.078 |
| 50.377   | 0.030 | 96.967 | 0.029 | 1.422                         | 0.011 | 1.112             | 0.005 | 30.484              | 1.065 |

Sample means and standard deviations

Target: Gimli

Mode: Tilt

All values in degrees





TABLE XII

| Location |       |        |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|--------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.   | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 18.501   | 0.051 | 95.998 | 0.093 | 1.538                         | 0.011 | 1.066             | 0.004 | -86.310             | 0.743 |
| 18.489   | 0.040 | 95.995 | 0.036 | 1.540                         | 0.012 | 1.065             | 0.004 | -86.469             | 0.714 |
| 18.499   | 0.059 | 95.977 | 0.105 | 1.542                         | 0.013 | 1.065             | 0.004 | -86.370             | 0.684 |
| 18.476   | 0.045 | 95.005 | 0.041 | 1.542                         | 0.012 | 1.065             | 0.004 | -86.600             | 0.557 |
| 18.491   | 0.055 | 95.968 | 0.129 | 1.540                         | 0.013 | 1.065             | 0.004 | -86.349             | 0.870 |
| 18.457   | 0.053 | 96.007 | 0.047 | 1.541                         | 0.011 | 1.065             | 0.004 | -86.454             | 0.657 |
| 18.463   | 0.051 | 95.984 | 0.100 | 1.542                         | 0.012 | 1.065             | 0.004 | -86.471             | 0.682 |
| 18.454   | 0.042 | 95.996 | 0.041 | 1.542                         | 0.012 | 1.065             | 0.004 | -86.437             | 0.630 |
| 18.450   | 0.065 | 95.966 | 0.142 | 1.544                         | 0.011 | 1.065             | 0.004 | -86.553             | 0.641 |
| 18.424   | 0.044 | 95.995 | 0.059 | 1.541                         | 0.011 | 1.065             | 0.004 | -86.509             | 0.654 |
| 18.422   | 0.049 | 95.988 | 0.042 | 1.545                         | 0.010 | 1.064             | 0.003 | -86.463             | 0.647 |
| 18.409   | 0.055 | 95.979 | 0.150 | 1.538                         | 0.013 | 1.066             | 0.004 | -86.558             | 0.632 |
| 18.406   | 0.043 | 95.995 | 0.051 | 1.543                         | 0.010 | 1.064             | 0.003 | -86.505             | 0.696 |
| 18.398   | 0.053 | 95.984 | 0.107 | 1.542                         | 0.011 | 1.065             | 0.004 | -86.424             | 0.667 |
| 18.387   | 0.059 | 95.970 | 0.106 | 1.542                         | 0.013 | 1.065             | 0.004 | -86.444             | 0.676 |
| 18.504   | 0.049 | 95.992 | 0.035 | 1.541                         | 0.010 | 1.065             | 0.003 | -86.369             | 0.663 |
| 18.501   | 0.047 | 95.998 | 0.045 | 1.542                         | 0.014 | 1.065             | 0.005 | -86.378             | 0.715 |
| 18.499   | 0.065 | 95.962 | 0.149 | 1.539                         | 0.011 | 1.066             | 0.004 | -86.288             | 0.743 |
| 18.492   | 0.054 | 95.980 | 0.054 | 1.540                         | 0.012 | 1.065             | 0.004 | -86.385             | 0.676 |
| 18.479   | 0.061 | 95.975 | 0.111 | 1.542                         | 0.012 | 1.065             | 0.004 | -86.337             | 0.753 |
| 18.466   | 0.065 | 95.968 | 0.175 | 1.538                         | 0.012 | 1.066             | 0.004 | -86.413             | 0.722 |
| 18.453   | 0.044 | 06.002 | 0.037 | 1.541                         | 0.010 | 1.065             | 0.003 | -86.449             | 0.600 |
| 18.451   | 0.058 | 95.991 | 0.089 | 1.541                         | 0.012 | 1.065             | 0.004 | -86.516             | 0.619 |
| 18.431   | 0.045 | 95.998 | 0.037 | 1.543                         | 0.010 | 1.064             | 0.003 | -86.480             | 0.721 |
| 18.429   | 0.053 | 95.996 | 0.071 | 1.542                         | 0.012 | 1.065             | 0.004 | -86.669             | 0.662 |

Sample means and standard deviations

Target: Veracruz

Mode: No tilt

All values in degrees



TABLE XIII

| Location |       |        |       | 90 Percent Confidence Ellipse |       |                   |       |                     |       |
|----------|-------|--------|-------|-------------------------------|-------|-------------------|-------|---------------------|-------|
| Lat.     | SD    | Lon.   | SD    | Major<br>Semiaxis             | SD    | Minor<br>Semiaxis | SD    | Axis of<br>Rotation | SD    |
| 18.588   | 0.067 | 95.868 | 0.220 | 1.565                         | 0.011 | 1.057             | 0.003 | -86.989             | 0.707 |
| 18.574   | 0.075 | 95.872 | 0.245 | 1.562                         | 0.009 | 1.058             | 0.003 | -87.139             | 0.595 |
| 18.568   | 0.087 | 95.858 | 0.256 | 1.562                         | 0.009 | 1.058             | 0.003 | -86.917             | 0.668 |
| 18.522   | 0.057 | 95.934 | 0.150 | 1.563                         | 0.010 | 1.058             | 0.003 | -87.028             | 0.569 |
| 18.516   | 0.063 | 95.952 | 0.126 | 1.562                         | 0.009 | 1.058             | 0.003 | -87.097             | 0.493 |
| 18.530   | 0.067 | 95.882 | 0.254 | 1.561                         | 0.009 | 1.058             | 0.003 | -87.129             | 0.724 |
| 18.506   | 0.046 | 95.963 | 0.073 | 1.566                         | 0.010 | 1.057             | 0.003 | -87.240             | 0.688 |
| 18.525   | 0.081 | 95.844 | 0.270 | 1.564                         | 0.011 | 1.058             | 0.003 | -87.087             | 0.601 |
| 18.497   | 0.058 | 95.909 | 0.195 | 1.567                         | 0.009 | 1.057             | 0.003 | -87.180             | 0.605 |
| 18.489   | 0.080 | 95.881 | 0.272 | 1.565                         | 0.012 | 1.057             | 0.004 | -87.211             | 0.709 |
| 18.483   | 0.067 | 95.904 | 0.175 | 1.564                         | 0.010 | 1.058             | 0.003 | -87.073             | 0.765 |
| 18.469   | 0.086 | 95.874 | 0.271 | 1.565                         | 0.010 | 1.057             | 0.003 | -87.189             | 0.648 |
| 18.460   | 0.077 | 95.887 | 0.239 | 1.566                         | 0.008 | 1.057             | 0.003 | -87.361             | 0.567 |
| 18.438   | 0.061 | 95.918 | 0.284 | 1.565                         | 0.009 | 1.057             | 0.003 | -87.299             | 0.548 |
| 18.441   | 0.062 | 95.927 | 0.169 | 1.567                         | 0.011 | 1.057             | 0.003 | -87.177             | 0.694 |
| 18.571   | 0.067 | 95.910 | 0.191 | 1.560                         | 0.010 | 1.059             | 0.003 | -86.989             | 0.529 |
| 18.544   | 0.043 | 95.970 | 0.062 | 1.560                         | 0.011 | 1.059             | 0.003 | -87.019             | 0.708 |
| 18.566   | 0.085 | 95.845 | 0.292 | 1.564                         | 0.009 | 1.058             | 0.003 | -87.135             | 0.739 |
| 18.539   | 0.075 | 95.935 | 0.152 | 1.563                         | 0.010 | 1.058             | 0.003 | -87.069             | 0.612 |
| 18.521   | 0.069 | 95.945 | 0.205 | 1.564                         | 0.011 | 1.058             | 0.003 | -87.157             | 0.656 |
| 18.531   | 0.069 | 95.899 | 0.222 | 1.564                         | 0.011 | 1.058             | 0.003 | -87.196             | 0.649 |
| 18.504   | 0.059 | 95.926 | 0.154 | 1.565                         | 0.012 | 1.057             | 0.004 | -87.072             | 0.523 |
| 18.502   | 0.057 | 95.918 | 0.197 | 1.564                         | 0.010 | 1.058             | 0.003 | -87.034             | 0.683 |
| 18.499   | 0.067 | 95.905 | 0.204 | 1.562                         | 0.010 | 1.058             | 0.003 | -87.089             | 0.643 |
| 18.472   | 0.056 | 95.968 | 0.095 | 1.565                         | 0.010 | 1.057             | 0.003 | -87.240             | 0.705 |

Sample means and standard deviations

Target: Veracruz

Mode: Tilt

All values in degrees



TABLE XIV

| No tilt<br>D(i) | Tilt<br>D(i) |
|-----------------|--------------|
| 54.883          | 54.836       |
| 54.773          | 54.781       |
| 54.932          | 54.828       |
| 54.826          | 54.838       |
| 54.796          | 54.818       |
| 54.841          | 54.825       |
| 54.837          | 54.842       |
| 54.860          | 54.836       |
| 54.848          | 54.831       |
| 54.876          | 54.860       |
| 54.799          | 54.880       |
| 54.792          | 54.899       |
| 54.808          | 54.869       |
| 54.835          | 54.956       |
| 54.856          | 54.885       |
| 54.848          | 54.758       |
| 54.866          | 54.839       |
| 54.865          | 54.810       |
| 54.882          | 54.832       |
| 54.856          | 54.816       |
| 54.901          | 54.826       |
| 54.894          | 54.832       |
| 54.920          | 54.838       |
| 54.912          | 54.859       |
| 54.937          | 54.897       |

Reduced location data  
for the Omaha samples



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| 13. ABSTRACT<br>It is generally accepted that the ionosphere tilts;<br>that is to say, an isoionic layer is not at constant height<br>above the surface of the earth. Ionospheric tilt has the<br>effect of deflecting a radio ray out of its great-circle<br>plane and returning it to earth at an angle not that of the<br>true bearing from a receiver to a transmitter. The magnitude<br>of error introduced by this effect on radio direction finding<br>(RDF) position estimates was studied in this paper. A model<br>assigning a tilt bias of less than three degrees to each<br>RDF station bearing was constructed. Analysis of a six-sta-<br>tion RDF network revealed that this amount of tilt has neg-<br>ligible effect on point estimates of location and their<br>confidence regions. |  |                                                                                             |                       |





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## KEY WORDS

## LINK A

## LINK B

## LINK C

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Direction Finding

Position Finding

Ionospheric tilt







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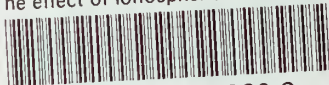
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